Near-barrier Fusion and Transfer/Breakup induced by Weakly Bound and Exotic Halo Nuclei

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The influence on the fusion process of coupling to collective degrees of freedom has been explored. The significant enhancement of the fusion cross section at sub-barrier energies was compared to predictions of one-dimensional barrier penetration models. This was understood in terms of the dynamical processes arising from strong couplings to collective inelastic excitations of the target and projectile. However, in the case of reactions where at least one of the colliding nuclei has a sufficiently low binding energy, for breakup to become an important process, conflicting model predictions and experimental results have been reported in the literature. Excitation functions for sub- and near-barrier total (complete + incomplete) fusion cross sections have been measured for the ^{6,7}Li+^{59}Co reactions. Elastic scattering as well as breakup/transfer yields have also been measured at several incident energies. Results of Continuum-Discretized Coupled-Channel (CDCC) calculations describe reasonably well the experimental data for both reactions at and above the barrier. A systematic study of ^{4,6}He induced fusion reactions with a three-body CDCC method is presented. The relative importance of breakup and bound-state structure effects on total fusion (excitation functions) is particularly investigated. The four-body CDCC model is being currently developed.

1. INTRODUCTION

In reactions induced by weakly bound nuclei, the influence on the fusion process of couplings both to collective degrees of freedom and to breakup/transfer channels is a key point for the understanding of N-body systems in quantum dynamics. Due to the very weak binding energies of halo nuclei, such as ^{6}He or ^{11}Be [1,2,3,4], a diffuse cloud of neutrons would lead to enhance fusion probabilities below the Coulomb barrier, where the neutron tail which extends well beyond the compact nuclear core provides a conduit by which the matter distributions of the target and projectile may overlap at longer range than for the core. In vicinity of the Coulomb barrier and below, the enhanced fusion with ^{11}Be was predicted [1]. On the other, the main enhancement effect for fusion with ^{6}He compared to its ^{4}He core may be due to the neutron rearrangement giving a gain in energy [5] as confirmed experimentally with ^{206}Pb and ^{197}Au targets [6]. However, recent experimental studies involving ^{6}He radioactive ion beams (RIB) [2,7,8,9,10,11] indicate that the halo of the ^{6}He nucleus does not enhance the fusion probability, illustrating the preponderant role of one- and two-neutron transfers (TR) in ^{6}He induced fusion reactions. Hence, the question of a real new effect with RIB's and with stable beams such as weakly bound ^{6}Li, ^{7}Li and ^{9}Be nuclei, namely the occurence of non-conventional transfer/stripping processes with large cross sections most likely originating from the small binding energy of the projectile, remains open [3,4].

Since the coupling between channels is known to enhance the fusion cross section at sub-barrier energies [1,3,4], coupled-channel (CC) effects have to be taken into account in the theoretical description of the fusion process. A large number of experimental results have been interpreted adequately well within the framework of CC calculations. However, in the case of loosely bound (and/or halo) systems the situation is more complicated since the breakup channel couples strongly to an infinite number of unbound states into the continuum [1,4,12]. A possible treatment of the problem is to reduce it to a finite number of channels. The traditional approach to discuss the sub-barrier fusion reaction induced by weakly bound nuclei is to solve the CC equations by discretizing in energy the particle continuum states in the projectile nucleus [1,12]. This is the so-called method of Continuum-Discretized Coupled-Channels (CDCC) that has been initially proposed by Rawitscher [13], and later developed for light heavy-ion reactions [14]. Experimental results [15] have well confirmed the calculations that fusion cross sections are significantly enhanced due to the couplings to the continuum states at energies below the barrier, while they are hindered above [1]. With the recent advent of new RIB facilities [3,6,7,9,10], it should be now possible to constrain more the parameters of the CDCC formalism [12]. Several studies have been initiated in this direction [16,17,18,19,20] to investigate reactions induced by the neutron halo of the borromean ^{6}He nucleus, which is known to have a strong dipole excitation mode.

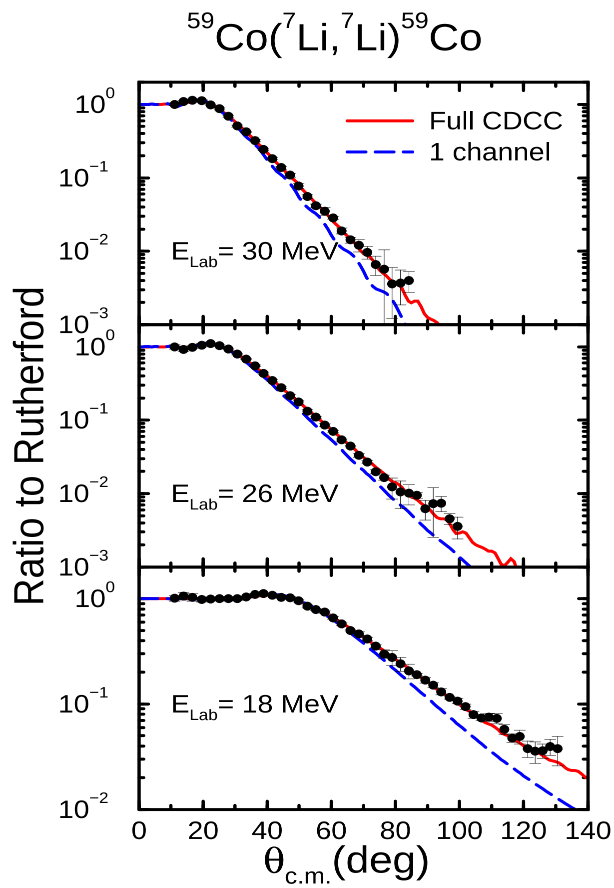

Figure 1: Experimental elastic scattering (data points) for ^{7}Li+^{59}Co [19]. The theoretical curves correspond to CDCC calculations [20] with (solid lines) or without (dashed lines) couplings with the continuum as discussed in the text.

In the recent past a CDCC calculation [18] failed to reproduce the large yields of α-particles reported in the ^{6}He+^{209}Bi reaction [7]. In this work we propose full CDCC calculations describing simultaneously elastic scattering (see Fig. 1), total fusion, and breakup of weakly bound light nuclei both stable (^{6}Li and ^{7}Li) and radioactive (^{6}He) with a medium-mass target (^{59}Co). Preliminary brief reports have been given elsewhere [19,20].

2. CONTINUUM-DISCRETIZED COUPLED-CHANNEL CALCULATIONS

CDCC, a fully quantum-mechanical method developed originally to study the effect of deuteron breakup on the process of elastic scattering [13], has been widely applied by the Kyushu group [14] to study heavy-ion collisions induced by light weakly bound nuclei. CDCC calculations have been successful in the past in describing the scattering of deuterons and ^{6,7}Li [14] on different targets. The CDCC method has been then applied to reactions with halo nuclei and, as a consequence, Diaz-Torres and Thompson [12] have been able to perform a full calculation of the theoretical fusion cross section of halo nuclei using a novel method still based on the CDCC formalism. A more recent study of the ^{6}He+^{209}Bi reaction by means of a three-body CDCC model [18] has shown much larger absorption cross sections than experimental fusion cross sections [7]. In the present work similar CDCC calculations are applied for the interaction of ^{6,7}Li and ^{6}He (with the simultaneous description of elastic scattering, fusion and breakup) with a medium-mass target such as ^{59}Co, and comparisons with the corresponding experimental data are presented.

Details of the calculations concerning the breakup space (number of partial waves, resonances energies and widths, maximum continuum energy cutoff, potentials, ...) have been given elsewhere [12,21], in particular in Tables I, II and III of Ref. [21]. The CDCC scheme is available in the general coupled channels (CC) computer code FRESCO [22]. All calculations were carried out using the version FRXX.09g of FRESCO [22]. Our choice was mainly influenced by the fact that we have already carried out extended CDCC calculations for both the ^{6}Li+^{59}Co and ^{7}Li+^{59}Co total fusion reactions [21] which data were previously published [23,24,25]. Before investigating that the proposed CDCC formalism can be also applied to halo nuclei such as ^{6}He, we present the full description of the $^{6}\mathrm{Li} \rightarrow \alpha+d$ and $^{7}\mathrm{Li} \rightarrow \alpha+t$ clusters as two-body objects, respectively, including elastic scattering angular distributions, total fusion cross sections, and breakup cross sections.

We would like to stress that in the chosen fusion calculations the imaginary components of the off-diagonal couplings in the transition potentials have been neglected, while the diagonal couplings include imaginary parts [21]. Otherwise full continuum couplings have been taken into account so as to reproduce elastic scattering data when available. We have used short-range imaginary fusion potentials for each fragment separately (α and d+target potentials and α and t+target potentials for ^{6}Li and ^{7}Li, respectively). This is equivalent to the use of incoming wave boundary conditions as performed in CCFULL calculations [23], for instance.

2.1. CDCC calculation of ^{7}Li+^{59}Co and ^{6}Li+^{59}Co elastic scattering

Results of the comparison of the CDCC calculations for the elastic scattering with the data [19,25] are shown in Fig. 1 and Fig. 2 for ^{7}Li+^{59}Co and ^{6}Li+^{59}Co, respectively. The two different curves are the results of calculations performed with (solid lines) and without (dashed lines) $^{6,7}\mathrm{Li} \rightarrow \alpha + d,t$ breakup couplings to the continuum (i.e. continuum couplings). The agreement is very good when full continuum couplings are taken into account. This was also found for the elastic scattering of both ^{7}Li+^{65}Cu and ^{6}Li+^{65}Cu reactions [26]. The effect of breakup on elastic scattering, stronger for ^{6}Li as expected, is illustrated by the difference between the one-channel calculations (equivalent to the optical-model OM calculations [25]) and the full CDCC results. The CDCC calculations using similar potentials that fit the measured elastic scattering angular distributions [25] of Fig. 2 are able to reproduce the breakup cross sections measured for ^{6}Li+^{59}Co [20,27]. For ^{6}Li the total calculated breakup cross sections, obtained by integrating contributions from the states in the continuum up to 8 MeV, are small as compared with total fusion CDCC [21] or experimental [23] (data points in the right panel of Fig. 3) cross sections.

The dynamic polarization potentials (DPP) generated by the coupling to breakup channels are determined by the CDCC method. The real and imaginary parts of the DPP are obtained at the three bombarding energies for ^{6}Li+^{59}Co and ^{7}Li+^{59}Co; their energy dependences appear to show the threshold anomaly only for the latter reaction. This preliminary conclusion will need to be confirmed by subsequent measurements at several other near-barrier energies.

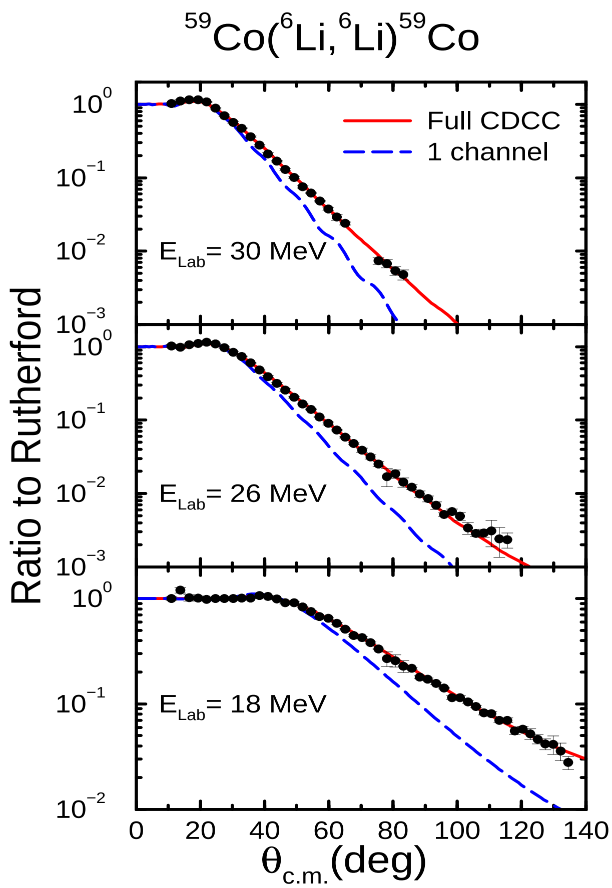

Figure 2: Experimental elastic scattering (data points) for ^{6}Li+^{59}Co [19]. The theoretical curves correspond to CDCC calculations [20] with (solid lines) or without (dashed lines) couplings with the continuum as discussed in the text (see Sec.2.1).

2.2. CDCC calculations of ^{6}He+^{59}Co fusion

In the following we present similar calculations applied for the two-neutron halo nucleus ^{6}He. The present case is much more complicated since ^{6}He breaks into three fragments (α+n+n) instead of two (α+d), and the CDCC method has not yet been developed for two-nucleon halo nuclei. Hence a di-neutron model is adopted for the ^{6}He+^{59}Co reaction: i.e. we assume a two-body cluster structure of ^{6}He = ^{4}He+^{2}n with an α-particle core coupled to a single particle, a di-neutron (^{2}n). Couplings to resonant (2^+, E$_{ex}$ = 0.826 MeV) and non-resonant continuum states (up to f-waves) are included. It is important to notice that the fact that the di-neutron is not an object with both fixed size and fixed energy (Heisenberg principle) might be a critical point in the present model.

The maximum energy of the continuum states is still equal to 8 MeV. Similarly to our previous work [21], the potentials between the fragments and the ^{59}Co target are those obtained with the global Broglia-Winther Woods-Saxon parametrization [28]. (the numerical values are: V$_o$ = -16.89 MeV, r$_o$ = 1.09 fm and a = 0.63 fm). For the α-2n binding potential (0^+, g.s.) we have used the following Woods-Saxon potential: V$_o$ = -40.796 MeV, r$_o$ = 1.896 fm and a = 0.3 fm. The g.s. binding potential of the α particle

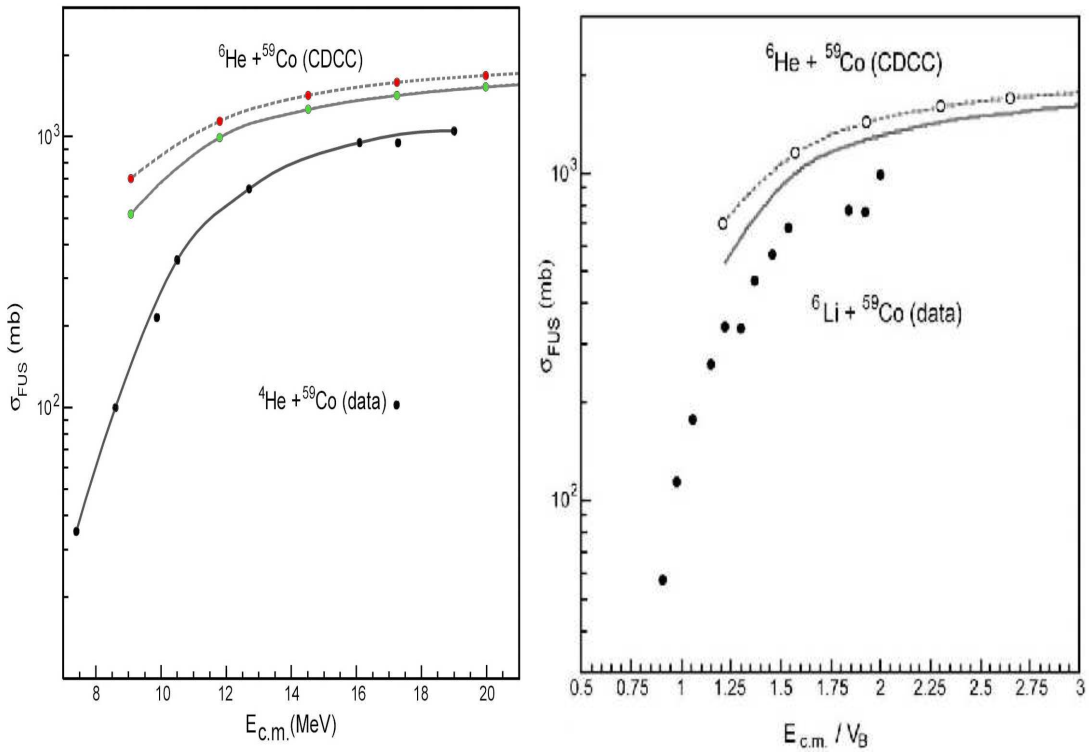

Figure 3. Total fusion excitation functions for ^{4}He+^{59}Co (data points [32] and solid black line for CC predictions on left panel) for ^{6}Li+^{59}Co (data points [23] on right panel), and for ^{6}He+^{59}Co. The curves correspond to CDCC calculations [21] for ^{6}He+^{59}Co with (dashed line) or without (thin line) couplings to the continuum as discussed in the text (see Sec.2.2).

and the di-neutron provides a 2s bound state of about -0.975 MeV. The binding potential of the 2^+ resonant state has also a Woods-Saxon form with the following parameters: V_o = -35.137 MeV, r_o = 1.896 fm, a = 0.3 fm. With this potential the energy of the 2^+ resonant state is 0.826 MeV and its width is 0.075 MeV. To obtain converged (within a 5% level) total fusion cross section we have included: (i) partial waves for α-2n relative motion up to f-waves ($l = 3$), (ii) the ^{6}He fragment-target potential multipoles up to the octupole term, and (iii) the maximum of the continuum energy is 8 MeV. All resonant and non-resonant continuum couplings including continuum-continuum couplings were included in the calculation. Results of the CDCC calculations for the fusion of ^{6}He+^{59}Co are compared to the ^{4}He+^{59}Co and ^{6}Li+^{59}Co systems in Fig. 3 and discussed below.

3. DISCUSSION

The proposed three-body CDCC model is adequate for ^{7}Li as well as for ^{11}Be, as long as core excitation is ignored; and, probably better than that for ^{6}Li. However the elastic scattering data [25] as plotted in Figs. 1 and 2 are very well reproduced for both ^{7}Li and ^{6}Li. It is interesting to note that the OM analysis [25] of their respective angular distributions was found to be ambiguous for the two lowest energies when using the parameter-free São Paulo OM potential [29]. The extracted total reaction cross sections [25] confirm the observed small enhancement (≈ factor 2) of total fusion cross section for the more weakly bound ^{6}Li nucleus at sub-barrier energies [23], with similar yields for both reactions at and above the Coulomb barrier in concordance with CDCC calculations [21]. This moderate enhancement effect observed below the barrier can be explained by the fact that both experimental [20,27] and theoretical breakup cross sections [20] are rather small (10-50 mb).

Without available data for ^{6}He+^{59}Co we have cautiously decided not to present CDCC calculations for the elastic scattering as the Coulomb dipole excitation is known to be too strong in the di-neutron approximation [18], and then difficult to be predicted. The dipole Coulomb excitation of ^{6}He projectiles in the field of a highly charged target has already been discussed [16,17,18]. The di-neutron CDCC model works much better when the dipole coupling strengh is reduced by 50 %. This reduction is important for heavy targets, but probably not as much for a medium-mass target such as ^{59}Co. Nevertheless, such reduction is also reducing total absorption cross section in the CDCC calculations. If we consider this cross section as the total fusion cross section, we may overestimate the fusion of ^{6}He+^{59}Co slightly. Obviously, the search for similar effects is of high interest for this medium-mass region [9], and elastic measurements with higher precision will have to be undertaken.

There is some confusion about the definition of fusion [21]. Theorists usually define complete fusion (CF) as the capture of all projectile fragments, and incomplete fusion (ICF) the capture of only some fragments [4]. Among other CC calculations, CDCC has the disadvantage of being unable to distinguish between CF and ICF [21]. In experiments a similar complication arises from the lack of a clear separation of CF and ICF cross sections [23]: therefore CF is defined experimentally as the capture of all the charge of the projectile by the target [23,30,31]. It is believed that there is a significant contribution of breakup followed by CF to the total fusion cross sections [4]. The combined effect of breakup and TR in the CC (CDCC) approach has not been fully studied so far in the context of sub-barrier fusion.

CDCC calculations using the set of parameters given for the ^{6}He+^{59}Co reaction in the previous Section are displayed in Fig. 3. The present calculations do not include neither target excitations nor TR channnels. However with crude estimations as those performed for the ^{6}Li+^{59}Co reaction [21] the effect is found to be very small. In Fig. 3 we compare the total fusion excitation functions of the two ^{6}He+^{59}Co (CDCC calculations) and ^{6}Li+^{59}Co (experimental data of Ref. [23]) reactions. For the ^{6}He reaction, the incident energy is also normalized with the Coulomb barrier V_B of the bare potential. The first calculation (solid line) only include the reorientation couplings in fusion without breakup. All contiunum and reorientation couplings are included in fusion with breakup (dashed curve). In agreement with heavier targets data [6], we can observe that both calculated curves (with and without breakup) give much larger total fusion cross section for ^{6}He as compared to ^{6}Li. We can also observe that the inclusion of the couplings to the breakup channels notably increases the total fusion cross section for the whole energy range. Similar conclusions are reached when ^{6}He+^{59}Co (CDCC calculations) is compared to ^{4}He+^{59}Co (here the CDCC calculations are fitting the data of Ref. [32] remarkably well) in Fig. 3.

4. SUMMARY AND OUTLOOK

Halo and cluster nuclei, with well-defined breakup and fusion modes, are good test-benches for theories of fusion and breakup. A more complete theoretical model of few-body dynamics that is able to distinguish CF from ICF will need to follow correlations after breakup, so we need either three-body (and most preferably four-body [34]) state-of-art CDCC [12,16,17,21] calculations of the type we have presented here as a starting point or, for instance, the use of a time-dependent wave-packet model [33].

The CDCC formalism, with continuum-continuum couplings taken into account, is most probably one of the most accurate method nowadays. Therefore, a systematic study of ^{4,6}He induced fusion reactions with the CDCC method is being undertaken. However up to now only very scarce studies with ^{6}He projectiles are available [2,6,7,8,9,10]: data from SPIRAL and Louvain-la-Neuve have recently been published for ^{6}He+^{63,65}Cu [10] and for ^{6}He+^{64}Zn [9]. The present extensive CDCC calculations show that for ^{6}He+^{59}Co considerable enhancement of the sub-barrier fusion cross sections is predicted as compared to measured fusion yields for both the ^{6}Li+^{59}Co [23] and ^{4}He+^{59}Co [32] systems. This conclusion is consistent with Dubna data for heavier targets [6]. We should note that contradictory theoretical results have been obtained for ^{10,11}Be+^{209}Bi collisions with a different approach based on the time-dependent wave-packet formalism [33].

The CDCC method [21], which is shown here to be quite succesfull for fusion with stable nuclei, will be used to provide the complete theoretical description of all competing processes (total fusion, elastic scattering, and breakup) in a consistent way. One really needs to investigate such processes in the dynamics of the interaction at the Coulomb barrier with loosely bound halo nuclei. The undertanding of the reaction dynamics involving couplings to the breakup channels requires the explicit measurement of precise elastic scattering data as well as yields leading to the TR (although TR cannot be described within CDCC) and breakup (and/or ICF) channels. The complexity of such reactions, whereby many processes compete on an equal footing, necessitates kinematically and spectroscopically complete measurements, i.e., ones in which all processes from elastic scattering to CF are measured simultaneously, providing a technical challenge in the design of broad range detection systems. A new experimental programme with SPIRAL beams and medium-mass targets is underway at GANIL within the forthcoming years [10,19,20].

While ^{6}He is best described as a three-body α-n-n object, at present the CDCC method has not yet been completely implemented for four-body breakup [34], its two-body α-^{2}n model appears to be rather satisfactory. The application of four-body CDCC models under current development [34,35] will then be highly desirable. In the longer term, four-body CDCC models might also be required for ^{6}Li, due to the possible sequential breakup of the deuteron. The questions in the theory of a halo system such as the borromean ^{6}He nucleus, its breakup (and in the breakup of many-body projectiles generally), and its CF and ICF processes will need the knowledge not just of those integrated cross sections, but the phase space distributions of the surviving fragment(s). Therefore, future very exclusive experiments performed at sub-barrier energies will have to determine very precisely the angular correlations of the individual neutrons. Preliminary attempts of measurements [8,11] of α-particles in coincidence with neutrons are promising to disentangle the effect of halo structures on the reaction mechanisms.

Aknowledgments: I would like to acknowledge N. Keeley and A. Diaz-Torres for their collaboration in performing the CDCC calculations. F.A. Souza is thanked for providing us with experimental data on breakup (cited in Refs. [20,27]) prior to their publication.

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